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Nano-ignition Torch Applied to Cryogenic H₂/O₂ Coaxial Jet

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Abstract

A high-pressure photoignition torch has been developed which takes advantage of the photoignition properties of single wall carbon nanotubes (SWNTs). The goal was to initiate combustion in a cryogenic O₂-H₂ coaxial injector at about 35 atm (~520 psi) at O₂ temperature of about 130 K with SWNT-based “solid fuel mixtures”. Our investigation includes the effects of chamber pressure, the presence of different solid oxidizers such as BKNO₃ and KMnO₄, as well as solid fuels and solid propellants, on the functionality of the photoignition torch. We have shown that the ignition parameters such as burn temperature, burn duration and the ignition byproducts can be tailored to meet different ignition requirements. It is anticipated that photoignition provides a suitable method for ignition of systems that require the start of combustion at a high pressure up to about 135 atm (2000 psi) as well as ignition of certain thrusters and liquid rocket engines that require an extremely small and light weight torch igniter. This ignition method can be applied to large combustion chambers such as gas turbines, gas generators, liquid rocket engines and possibly multi grain solid rocket motors.

I. Introduction

There are a number of properties that are desirable for an ignition system. Ideally an ignition system should be robust, efficient, reliable, simple, low cost, and flexible. Ideally, an ignition system should initiate combustion under a broad range of conditions in order to maximize the operational flexibility of energy and propulsion systems. When ignition systems rely on high reactivity additives, such as hypergolic or pyrophoric reactants, handling and storage of these specialized chemicals may be complicated by safety and health concerns. Thus there is a need for novel ignition technologies that satisfy the numerous requirements while maintaining simplicity.

Ajayan et al. first reported the photoignition of single-wall carbon nanotubes (SWNTs) by a camera flash in 2002.¹ It was suggested that Fe nanoparticles within SWNTs play an important role in the photoignition process.² Subsequently, others reproduced some of the aforementioned results³ and we suggested that SWNTs could be used as an ignition agent for a variety of fuels, including those of interest in liquid rocket engines.⁴⁻⁶ Other applications of photoignition of SWNTs have also been reported.⁷⁻¹⁰ More recently, research on the photoignition of gaseous fuel and air mixtures showed distributed ignition.^{11,12} Photoignition of graphene oxide for fuel burning applications has also been demonstrated.¹³

An ignition torch that is based on the photoignition of carbon nanotubes was developed and ignition of liquid fuel sprays by the torch has been achieved. In this report, we will describe the experimental procedure for producing ignition that is induced by a compact Xe-flash, including the results for photoignition of a simple fuel spray in air as well as ignition of a coaxial injector flow with cryogenic propellants. The application for the current effort is liquid rocket engines, but the reported photoignition torch has a range of other possible applications beyond propulsion systems.

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II. Experimental Setup

Samples of SWNT with different nanoparticle Fe content used in this study were obtained from Unidym Inc., Houston, Texas. The samples were as-grown SWNTs with a high concentration of impurities as byproducts of CNT syntheses. Based on the evidence presented by the vendor the carbon nanotubes believed to be predominantly SWNT. The as-grown samples typically contain substantial impurities, (about 50% by weight in the reported samples) mostly Fe nanoparticles and amorphous carbon.^{3,14} The term CNT is used for the samples in this report in order to indicate that they were as-grown SWNT samples and they were not purified in any way. Contrary to photoignition, most applications of CNTs require high concentration of CNTs and low concentration of Fe, which explains the need for the often elaborate purification process. However, purified samples show considerably higher photoignition threshold as tested, thus ill-suited for photoignition applications. The same batch of CNT was used for all photoignition experiments reported here, the CNT samples with nanoparticle Fe content of 51 wt.%, as stated by the vendor. In most cases some solid additives (to be described later) were used along with CNTs, which are collectively referred to as a "CNT mixture."

The ignition light source was a modified version of the compact Xe-flash that is used in a disposable camera. This type of light source proved to be quite reliable and the Xe-flash bulb was found to have sufficient structural integrity for high pressure applications, and survived many pressure cycles between 1 to 135 atm. Also, the same Xe-flash unit was repeatedly used for ignition at elevated pressures up to about 50 atm.

Figure 1 shows the preferred configuration of a self-contained Xe-flash light source, the related electronics, and a transparent ignition capsule that is partially filled with the CNT mixture. Similar ignition capsules were used in all of the configurations reported here. When used within a pressure vessel, the Xe-flash and the ignition capsule were usually placed next to each other under high pressure and connected through sealed feed-through electrical wires to the rest of the electronics outside.

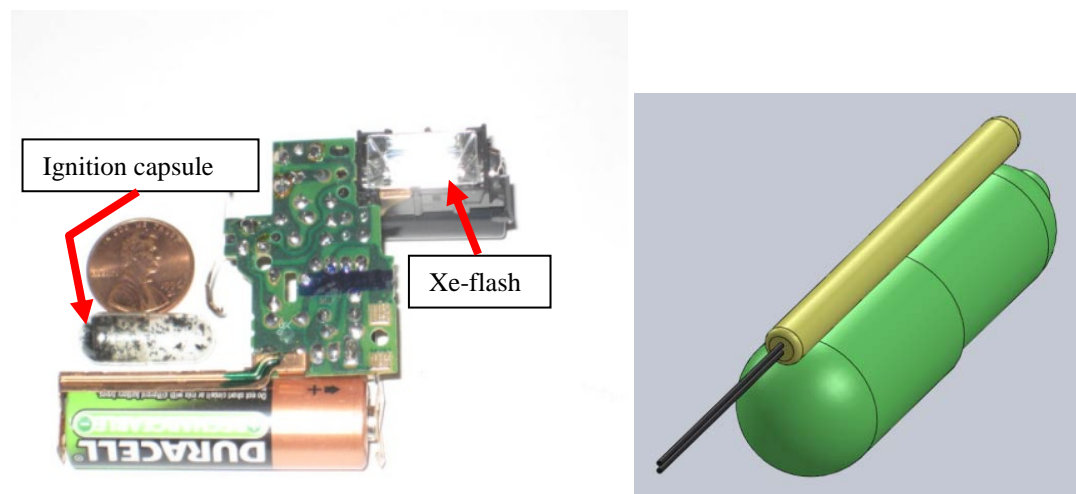


Figure 1 – The photographic image of a complete hardware of a self-contained photoignition device that was used in most of the reported ignition systems and torches. The ignition capsule that is shown below the penny is 5-10% filled with 30-70 mg of the nanostructured solid fuel mixture. Normally the capsule is placed alongside of the Xe-flash that is shown at the top right where it receives the maximum exposure.

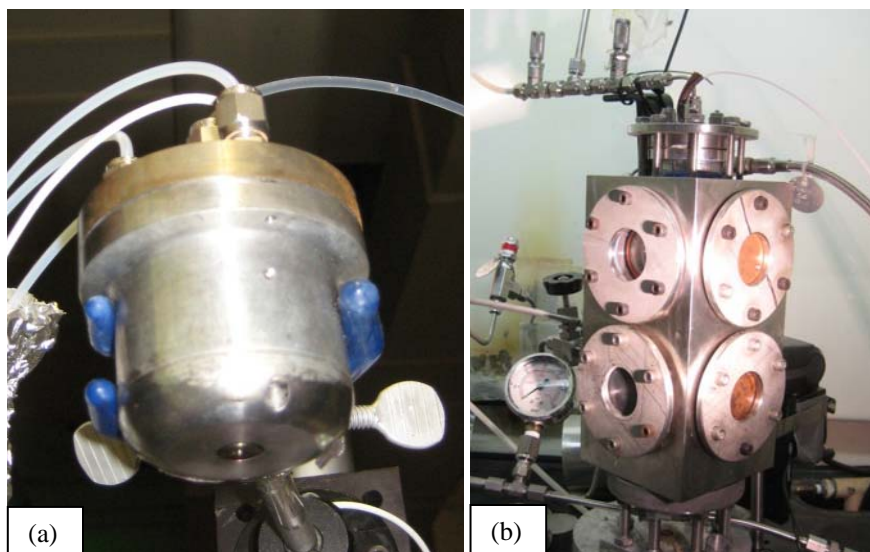


Figure 2 – (a) The customized ultrasonic atomizer (OD=6 cm) that was used as the fuel injector at atmospheric pressure and at an intermediate pressure up to about 30 atm (~450 psi). (b) The mid-pressure combustion chamber for photoignition test up to about 30 atm (440 psi) of pressure with the ultrasonic fuel injector at the top of it. In this case the light source is located outside of the chamber against the lower back window (D=5 cm, L=2.5 cm) and the ignition torch sits inside the chamber and against the same window.

Experimental Setup for Fuel Spray Ignition

Three different setups were utilized for the fuel ignition experiments. The first one was used for observation of the dynamics of the photoignition process at atmospheric pressure with an unhindered view of the ignition source and the ignition process. Figure 2 shows a picture of the ultrasonic atomizer that was used to produce an injector flow for some of the ignition studies. It also shows the second fuel ignition setup, a mid-pressure test chamber that was utilized to observe the torch function up to about 30 atm. The pressurizing gas was N₂, air, or a combination of the two for reduced oxidation capability, and it included both stagnant and flowing conditions.

The third setup was a compact high-pressure ignition torch (HPIT) chamber that was made of brass and was designed for photoignition experiments up to about 135 atm of pressure. Figure 3 shows a schematic diagram of HPIT along with photographic image of the HPIT as it is attached to high pressure combustion chamber that uses HPIT through a 30 cm long connecting tube. The HPIT was utilized to ignite the O₂-H₂ at different pressures and temperatures.

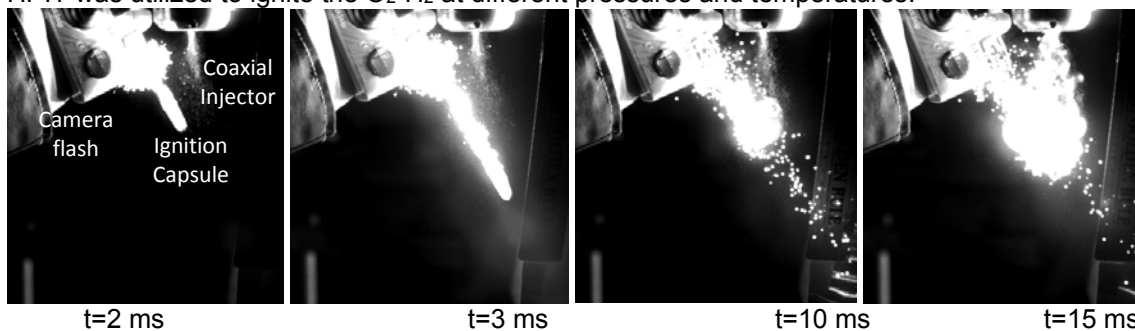


Figure 3 – Photoignition of RP1 spray by a nano-ignition capsule containing about 5 mg of CNT shows the process through the sequence of images. In this case the ignition capsule is taped on the flash of a disposable camera that is also shown. The time reference of t=0 indicates the peak of the illumination of the disposable camera flash with a duration of about 1 ms. The fuel injector is the customized ultrasonic atomizer that is shown in Figure 2(a). These images were captured at 2000 fps.

III. Instrumentation

A high-speed pyrometer, model KGA 740 HS from Mikron Infrared Inc., covering a temperature range from 300-2300 C was used to determine the instantaneous temperature of the sample during the process leading to photoignition of the CNTs, as well as for measuring burn temperature of other ingredients such as aluminum nanoparticles and solid rocket fuel particles. It should be noted that the pyrometer produces a curve of the instantaneous temperature of a focused spot of the sample that is about 2 mm in diameter that also provides a reasonable estimate of the maximum burn temperature of the sample. As such the reported values are a rough measure of maximum burn temperature of the spot on the surface of the sample and they may not represent the true temperature of the entire sample.

A high-speed Phantom V7.1 camera from Vision System capable of capturing up to 4800 frames/s (fps) at full-frame (800x600) was utilized in most of the experiments to record the sequence of ignition events, including fast moving photoignition byproducts. In the HPIT experiments, a different high-speed camera, model Phantom V710 from Vision System (7500 fps at 1280x800) was utilized.

IV. Experimental Procedure

The motivation for this project was to use CNTs as photoignition agents for initiation of combustion in subscale liquid rocket fuel injectors. The general approach is to take advantage of the exothermic photoignition of carbon nanotubes to initiate combustion within reactants mixed with the nanotubes. The current approach goes beyond the general practice and involves an ignition chamber which is separate from but connected to the combustion chamber.

The Need for Encapsulated CNT

Previous proof-of-concept experiments indicated that this could be a viable approach. However, it was observed that samples that were partially wet due to exposure to the mist from the liquid fuel spray required a substantially higher light fluence (energy per unit area) for photoignition. The high fluence requirement made photoignition of fuel sprays very difficult to implement for most applications, because the CNT sample is usually located close to the fuel spray in order to induce ignition.

In order to overcome the problem two methods were devised to keep the CNT samples dry. The first method was encapsulation of CNT mixture in a transparent container/capsule, and the second one was lamination of CNTs along with a solid oxidizer in thin layers of a transparent polymer. Both methods proved to be effective, but the encapsulation is more reproducible and it is easier to implement for high-pressure applications. Thus encapsulation of CNTs along with solid energetic additives, referred to as CNT mixture was employed as the method of choice for igniting liquid fuel/oxidizer flows. Examples of CNT mixtures are presented in Table 1 and a detailed description of the purpose and properties of different CNT mixtures will be discussed later in this report.

The ignition capsules were prepared by placing CNT mixtures in a transparent gel cap size 00 (about 0.75 cm³ in volume, D=7 mm and L=20 mm). Figure 1 shows a typical ignition capsule partially loaded with CNT mixture. Numerous tests indicated that if there was sufficient material in the container, typically a few milligrams, the gaseous byproducts of the photoignition of CNT (mostly CO₂ and CO) would pressurize the capsule beyond its 2 atm (~30 psi) limit, causing it to burst and release its burning contents to ignite the fuel spray.

Results and Discussions

Photoignition of Different Materials

We studied ignition characteristics of CNT and a number of other nanoparticles or nanostructured materials in order to identify those parameters that are particularly useful in photoignition process. The parameters of interest are minimum ignition energy (MIE) and burn temperature for different materials, as listed in Table 1. We also studied photoignition properties of other materials such as multi-walled CNT, C60 fullerenes and SWNT and multiwall carbon nanotubes from different vendors as well as carbon black, metallic and nonmetallic fine particles, and ball milled metallic thermites with mixed results. Table 1 only includes materials that are well characterized and showed a more consistent photoignition effect. The stated error figures are the measured statistical variations for the first four samples and they are the estimated uncertainty for the last three samples.

Table 1 – MIE for different nanostructured materials and their corresponding burn temperatures

nanoparticle samples	particle size/ smallest dimensional size	Min. ignition Energy/area, Fluence (mJ/cm ²)	ignition/burn temperature* (°C)
CNT(51% Fe)	< 30 nm	64 ± 8	490 ± 30
CNT(18% Fe)	< 30 nm	182 ± 13	420 ± 50
Graphene Oxide Foam/Nanoplatelets	< 30 nm thick platelets	500 ± 60	370 ± 100
Al-nanoparticles	18 nm	290 ± 50	1100 ± 150
Fe, Carbon coated	~ 40 nm	220 ± 35	250 ± 30
Fe powder	~ 30 nm	150 ± 25	220 ± 30
Pd powder	~ 12 nm	530 ± 60	320 ± 40

*This is the temperature of a focused spot on the sample and may not be representative of the entire sample.

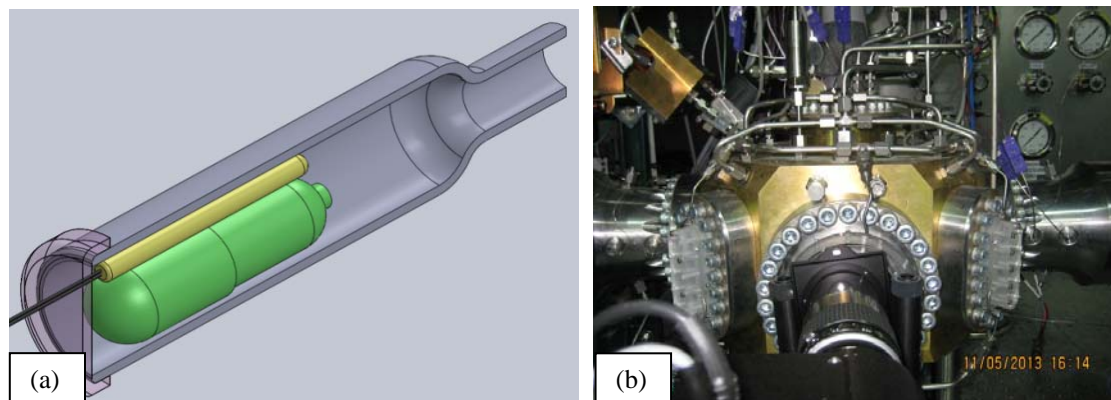


Figure 4 – (a) The schematic diagram of the drop-in 135 atm (2000 psi) ignition torch. The ignition capsules are loaded from the back and hot gas and burning particles rush through the tube (OD=6 mm) in front of the torch. (b) The O₂-H₂ combustion chamber that is designed for combustion instability studies at pressures up to about 100 atm. The high-pressure ignition torch, the brass cube on the top left corner of this photographic image is coupled to the combustion chamber via a 35 cm long tube with OD=6mm.

Realization of the Photoignition Torch

In preliminary tests, nano-ignition capsules were used to ignite a fuel spray by allowing the two-part capsule to burst open in the vicinity of the fuel spray. In this report the term fuel spray is used in its most

general sense so that it includes injector flow as well, though from technical point of view they may not be the same as it is related to the presence or flow of the oxidizer. Further investigations of fuel ignition process revealed that a 2-3 mm size hole in an ignition capsule may prevent it from exploding due to over pressurization, if the burn rate was kept sufficiently low. In such cases the capsule would discharge burning byproducts and burning particles directly through the hole as the pressure is built up in the capsule. Hence it produces a miniature ignition torch. An example of the application of photoignition torch for fuel spray is shown in Figure 4.

At atmospheric pressure, a typical photoignition torch may burn close to 0.5 second depending on the burn rate and the amount of fuel in the capsule, and it typically discharges a combination of hot gas, flame, and burning particles that extends 15-30 cm away from the ignition capsule. As the ambient pressure is increased beyond about 10 atm, the burn rate gradually increases and the burn duration decreases, so that at about 30 atm the burn duration is no more than half of what it is at 10 atm for most CNT mixtures. This trend is expected to continue as the pressure is increased beyond 30 atm.

Table 2 – Ingredients for a photoignition torch for different chamber pressures.

CNT, main Photoignition Agent (Wt%)	Fuel Al_NP 18/80nm (Wt%)	Fuel SRF (Wt%)	Oxidizer BKNO₃ (Wt%)	Oxidizer KMnO₄ (Wt%)	Observations and Comments On the Relative Effects of Additives
Sample 0 100%					Short burn duration & low burn Temp. (~800K)
Sample 1 10%			90%		Improved ignition reliability & burn Temp.
Sample 2 10%				90%	Reliable ignition only >10 atm
Sample 3 ~3%		~97%			Unreliable ignition of SRF associated with a long ignition delay (ratio doesn't matter)
Sample 4 3%	7-12%	85-90%			More reliable ignition, burns at higher T & is more energetic than samples 2 & 3
Sample 5 3%	7%	45%		45%	Less reliable ignition than the above unless the chamber Pres. >10 atm
Sample 6 3%	7%	50%	40%		Improved flash sensitivity & ignition + generate a lot of gas & smoke
Sample 7 1%	9%	80%	10%		Best ignition sensitivity, reliability & burn duration for chamber Pres. >7 atm
Sample 8 2%	8%	70%		20%	Comparable to sample 7 only for chamber Pres. >15 atm
Sample 9 2%	8%	70%	20%		Improved ignition reliability and burn duration
Sample 10 1%	15%	75%	9%		As good as the above at atmospheric pressure, but burns too fast >15 atm

Fuel Mixtures for a Photoignition Torch

While we were able to ignite a fuel spray with an ignition capsule that contained only CNTs, such an ignition capsule exhibited a number of drawbacks. These are due to the fact that CNTs do not burn long and hot enough and the amount of gas generated may not be sufficient for an

effective ignition torch for most applications. The solution was to add small amounts of granulated solid fuel/propellants and oxidizers to the ignition capsule. The CNTs would ignite these additives and then the much more robustly burning additives could be used to ignite something else. Table 2 shows examples of ingredients of a typical ignition capsule along with the weight percentage of each of the ingredients in the capsule. Comments about the relative advantages and possible disadvantages of each specific mixture are also stated in Table 2.

It should be mentioned that each material in Table 2 is from the same batch and the total content of the photoignition torches were typically 30-70 mg. CNT samples with no add material as well as samples with added energetic materials such as aluminum nanoparticles (Al-NP) solid rocket fuel (SRF) and solid oxidizers were used as fuel for the photoignition torch. The different CNT mixtures exhibited different ignition properties depending on their ingredients. A rough measure of burn temperature and qualitative burn duration of various CNT mixtures were determined through the pyrometer as described previously. The burn duration of most photoignition torches were also measured by the high-speed camera, which is a more reliable approach.

All of the ingredients that are listed in Table 2 are commercially available except for the solid rocket fuel (SRF), also known as solid propellant, which is formulated and prepared in-house. The SRF is typically 87% solid loaded composite propellant composed of hydroxyl-terminated polybutadiene (HTPB) as a binder, ammonium perchlorate as an oxidizer and aluminum powder as a fuel. The granulated SRF was used in the ignition capsules that are reported here and they were made from rubber-like solid chunks of SRF that is mixed from solid powders and polymerized through a proprietary process at the Air Force Research Laboratory Edwards AFB. It is possible to use commercially available model rocket fuels (MRF) instead of SRF. While MRF is easier to ignite and it typically produces more gas than SRF, it also produces black smoke and leaves behind a film residue on the nearby surfaces. Moreover, MRF in powdered form burns too fast at elevated pressures and it may be hard to produce properly sized particles from this material if it is not polymerized.

At elevated pressures, it may be necessary to push the photoignition byproducts from the ignition chamber into the combustion chamber with pressurized air/gas before they burn out. This is not necessary when the photoignition torch is placed inside the combustion chamber. In ignition experiments with HPIT, an air pressure of 2-4 at above the combustion chamber pressure was used in order to carry ignition byproducts to the high-pressure combustion chamber before they were extinguished. The best photoignition torch for 20-50 at pressure has been generated by samples 7 through 10 in Table 1, respectively.

A typical nano-ignition capsule has a total mass of no more than 200 mg, of which about 130 mg is due to the empty capsule and the rest is the CNT mixture. The amount of CNT in the mixture is typically 1-3 mg. The function of the solid oxidizer is to speed up the propagation of ignition to other solids. For the solid oxidizer, boron-potassium nitrate (BKNO_3) and potassium permanganate (KMnO_4) were used. While technically BKNO_3 is not merely an oxidizer, but a mix of fuel (boron) and oxidizer (KNO_3), we used it as an oxidizer.

The role of Al-NP is to make sure that the temperature increases rapidly enough and gets high enough (exceeding 1500 K) to ignite the SRF. We used Al-NP in powdered form with nominal sizes of 18 nm and 80 nm and found both of them to be equally effective as additives for the reported application. The only notable difference between the two is that the former exhibits photoignition without CNT and latter does not show such a property up to the maximum fluence that was available to us, about 3 J/cm². SRF is the main ingredient that provides a burn duration beyond 200 ms and a burn temperature well beyond 2000 K. We were able to achieve burn durations approaching 1 s at atmospheric pressure by utilizing the same capsule size of Figure 1 and the same ingredients of Table 2 with no more than 150 mg of CNT mixture. A typical photoignition torch has about 30-70 mg of CNT mixture and burns for 200-400 ms at atmospheric pressure and for 50-100 ms at about 50 atm.

Fuel Spray Ignition at Ambient Condition

The setup of Figure 2(a) was used for fuel spray ignition in open air under a fume hood. In the liquid fuel burning experiments, an ignition capsule was positioned close to the path of fuel spray from the ultrasonic atomizer, such that upon ignition and rupture of the nano-ignition capsule the fuel and the burning particles impinge upon one another. The camera flash was located very close to the ignition capsule so that it received sufficient energy from the flash to induce photoignition of the CNT mixture. The photoignition and subsequent fuel ignition and burning process were captured by a high-speed camera, at a rate of 500-2000 frames/second (fps). Figure 3 shows still images of a fuel burning experiment at atmospheric pressure after the activation of the camera flashed. Within 10 ms the combustion of the fuel spray is in progress through the expanding fireball that is about 4 cm in diameter. The flame speed is several meters per second, depending on the fuel and within 15 ms the entire combustible mixture is in flame.

Ignition Torch for Combustion of Injector Flow at Elevated Pressures

The setup of Figure 2(b) was used to study photoignition at an elevated pressure up to about 30 atm. In this case, the compact Xe-flash light source was outside of the chamber and the ignition capsule was inside, and the light coupling was made available through a 5 cm wide quartz window at a bottom port opposite to the high-speed camera. The byproducts of the ignition were directed upward toward the fuel spray and the injector flow. The ultrasonic atomizer was modified to accept a pressurized fuel line. The pressure in the chamber was provided by a high pressure air bottle. The exhaust port was at the bottom of the chamber directing the flow and hot gas through a cold trap. Ignition of different types of fuels with this set up was demonstrated including isopropyl alcohol (IPA), methanol and RP1, a category of aerospace fuel similar to kerosene.

In order to use a photoignition torch for high pressure applications, a high-pressure ignition torch (HPIT) with a separate ignition chamber was designed and built. Figure 4 shows a schematic diagram of a HPIT that is capable of sending hot/reacting gases and burning particles beyond 35 cm from the ignition capsule. The body of HPIT is made of brass in order to safely operate at high pressure in an oxygen-rich environment up to about 135 atm (2000 psi). High pressure air is introduced to the HPIT from a K-bottle through an inlet such that the pressure within the ignition chamber stays 2-3 atm above the pressure in the combustion chamber. This excess pressure provides a continuous gas flow in order to carry the hot photoignition byproducts into the combustion chamber and provide the opportunity for fuel ignition at the combustion chamber. The entire system was housed in an explosion proof facility with the remote operation capability that provided control signals for the different remote operated valves and electrical firing sequence with millisecond accuracy.

We have successfully applied the HPIT system to generate ignition of an O₂-H₂ coaxial shear injector flow at elevated pressures up to ~35 atm. The coaxial shear flow had liquid oxygen in the center tube and gaseous hydrogen in the annular outer tube. Figure 5 shows an example of initiation of O₂-H₂ combustion that is made possible by a photoignition torch. In a typical high-pressure O₂-H₂ combustion experiment, the timing sequence is controlled such that the burning particles arrive at the coaxial jet region within a few milliseconds before H₂ enters the chamber in order to prevent the accumulation of unburned fuel within the chamber. Typically the combustion of fuel happens within a few milliseconds after burning particles first show up in the combustion chamber and the combustion is typically limited to a few seconds in order to avoid overheating and possible melt down of the injector. However combustion can be sustained as long as it is needed for the study, up to 12 s as tested, with no sign of any damages to the injector.

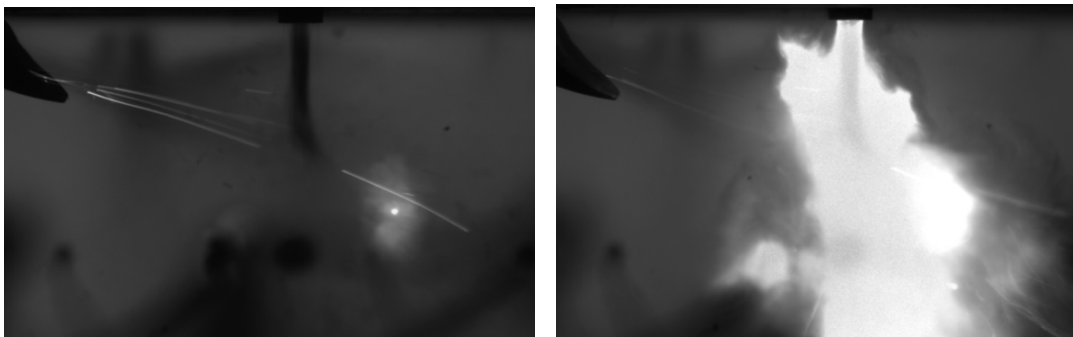


Figure 5 – Snapshots of combustion in LOX/H₂ coaxial jet that was induced by a photoignition torch at ~32 atm and ~133K. The exit point of the burning particles from the 35 cm long tube of the ignition torch is located at the top left corner of the image. These images show $t = T+1$ ms and $T+2$ ms after firing of a Xe-flash that has a pulse duration of 1 ms, where $T=25-30$ ms is the delay between ignition signal and the burning particles entering the combustion chamber. The field of view is about 7 cm across and the images are captured at 1000 fps.

Tailoring Ignition Parameters for Fuel Ignition Applications

The function of CNTs is to provide photoignition at a low light level (less than 0.1 J/cm^2), while producing substantial amount of gas to pressurize the capsule.^{6,15} This event sets off a chain reaction that ruptures the two part capsule that typically bursts open at about 2 atm of static pressure. Aluminum nanoparticles (Al-NP) in the fuel was easily ignited by burning CNTs (about 800 K) and it produced a high burning temperature (exceeding 1500 K), which lasted more than 100 ms.¹⁵ It is worth mentioning that 18 nm Al-NPs showed photoignition at high enough fluence ($> 0.6 \text{ J/cm}^2$) without any CNTs.¹⁵ However Al-NPs produce very little gaseous byproducts, certainly not enough to contribute to the pressure build up within the ignition capsule.

Aluminum nanoparticles burn much longer than CNTs and burn at a high enough temperature to ensure the ignition of SRF particles. In turn SRF particles burn at a very high temperature, well above 2000 K, they produce a substantial amount of gas and burn for a substantially longer time, exceeding 500 ms, depending on their size and their surface to volume ratio. Through many tests, it was verified that a combination of the ingredients in Table 1 provides the capability of tailoring the burn temperature, pressure ramp up and burn duration for different applications.

A 200 mg photoignition torch can release numerous burning particles at the exit tube of the torch that is 35 cm away from the ignition capsule. The smallest torch that was able to produce consistent ignition contained about 10 mg of fuel mixture and was able to introduce hot/reacting gases and burning particles 10-15 cm away from the ignition capsule. Burn duration of an ignition capsule is adjustable between 50-1000 ms at atmospheric pressure depending on the type and the amount of its ingredients. A noticeable reduction in burn duration has been observed at elevated pressures beyond 10 atm.

V. Conclusions

A miniature photoignition torch using an encapsulated CNT-based fuel mixture was created. The photoignition torch has been tested up to about 135 atm (2000 psi) of pressure and its suitability for spray ignition demonstrated up to ~50 atm (~735 psi). Application of the photoignition torch for initiation of combustion in a cryogenic O₂-H₂ shear coaxial flame at high pressure was demonstrated at an oxygen temperature of about ~130 K and a pressure of ~32 atm (~470 psi). The photoignition torch as described is suitable for high pressure ignition applications. It also offers the following advantages:

- Light weight and compact: A typical self-contained ignition system has a mass of less than 25 g without the battery and it occupies less than 30 cm^3 of space. The ignition capsule is about 200 mg and it contains 50-70 mg of fuel.
- Safety: The photoignition torch is battery operated and optically coupled so that there is no electrical contact between the ignition source and the ignition charge or fuel. This makes a

photoignition system relatively insensitive to electromagnetic interference and electrostatic discharge.

-Reliability: The photoignition torch is based on the mature technology of a compact battery operated Xe-flash lamp and ignition of solid propellants. Over the course of 4 years of testing, the Xe-flash has shown no reliability problem.

-Scalability: While the photoignition torch has been demonstrated here only at small scales, the photoignition system can be easily scaled up to much larger sizes with a relatively small penalty in the ignition delay.

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